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Mathematical Model for Fabric Filtration with Integral Particle Charging and Collection in a Combined Electric and Flow Field

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A MATHEMATICAL MODEL FOR FABRIC FILTRATION WITH INTEGRAL PARTICLE CHARGING AND COLLECTION IN A COMBINED ELECTRIC AND FLOW FIELD

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16. ABSTRACT The paper describes a mathematical model for fabric filtration with integral particle charging and collection in a combined electric and flow field. The model computes the non-uniform dust cake formation as a function of the average gas-to-cloth ratio, bag diameter and length, electrical conditions (voltage and current), and particle size distribution. The non-uniform deposit is the sum of the electrostatic precipitation (ESP) and the porous flow collections. The dominant collection is the ESP effect. The model also computes the relative pressure drop of the electrified bag as compared to a conventional non-electrified fabric filtration bag using the assumption that the drag or resistance to flow for a specific particle dust cake is proportional to the areal density. The model was used to compute the relative pressure drop for two pilot units which compared with reasonable accuracy to measured performance. The model is useful as an engineering tool for predicting performance for fabric filtration baghouses using integral particle charging and collection and can be applied to any further development of the technology that may be undertaken.

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A MATHEMATICAL MODEL FOR FABRIC FILTRATION WITH INTEGRAL PARTICLE CHARGING AND COLLECTION IN A COMBINED ELECTRIC AND FLOW FIELD

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ABSTRACT. Fabric filtration in the form of baghouses is an old technology used for separation of particles from gas streams prior to discharge into the atmosphere. To improve performance of the fabric filtration process, various experimenters have shown that electrically charging the particles before collection on the fabric media (or developing an electric field at the fabric collecting surface) lowers the pressure drop across the dust cake.

To take maximum advantage of the pressure drop reduction benefits of electrification, a practical system has been devised to provide integral particle charging and collection in a combined electric and flow field. This system makes use of an electrode wire axially located in each bag. An electric field is developed between the wire and the bag surface. The wire is caused to go into corona to charge the particles. The non-uniform dust cake that is deposited has its maximum thickness at the bag inlet. The pressure drop across the dust cake with electrification is less than for the uniform dust cake that results from non-electrified filtration.

A series of laboratory experiments indicated that the increase in face velocity with decreasing dust cake thickness is linear with position in the bag. It was also seen that the drag, or resistance to flow, was related to dust cake areal density. No relationship was noted between dust cake bulk density and resistance to flow.

A mathematical model was developed that computes the non-uniform dust cake formation as a function of the average gas-to-cloth ratio, bag diameter and length, electrical conditions (voltage and current), and particle size distribution. The non-uniform deposit is the sum of the electrostatic precipitation and the porous flow collections. The dominant collection is the electrostatic precipitation effect. The mathematical model also computes the relative pressure drop of the electrified bag as compared to a conventional non-electrified fabric filtration bag using the assumption that the drag or resistance to flow for a specific particle dust cake is proportional to the areal density. The mathematical model was used to compute the relative pressure drop for two pilot units which compared with reasonable accuracy to measured performance.

The mathematical model that has been developed is useful as an engineering tool for predicting performance for fabric filtration baghouses using integral particle charging and collection and can be applied to any further development of the technology that may be undertaken.

1. INTRODUCTION AND BACKGROUND

Fabric filtration in the form of baghouses, one of the principal technologies for the removal of particulate matter from gas streams, has been used for many years by various industries. In recent years, in response to increasingly stringent air pollution control requirements, baghouses have gained more prominence, especially in the electric power industry. The majority of electric power plants with baghouses use inside-to-outside flow. In the United States in 1984 there were over 110 baghouses associated with more than 20,000 MW of electric generating capacity.[1] Electrostatic precipitators are used in the majority of the utility plants. However, interest in baghouses for electric utility application is increasing. In a typical application, gas flow is arranged for inside-to-outside flow with the dust collected on the interior

of the bag. The work described in this paper is for inside-to-outside flow which is used for all coal-fired utilities in the United States and many of the high volumetric gas flow applications in other industries.

For inside-to-outside-flow fabric filtration bags, woven fabrics are usually used. Woven fabrics have pores that are large in comparison to the size of the particulate matter or dust that is to be filtered. Their filtering action depends on the building up of a dust cake, which actually performs the filtration, on the surface of the fabric.

To make a practical filtration system, some means must be introduced for cleaning the accumulated dust from the bags to maintain the pressure drop within the fan operating limits. For the inside-to-outside flow method this cleaning is done by reversing the gas flow, mechanical shaking, or some combination of both. Filtration is a continuing process consisting of dust accumulation and cleaning, followed by another period of dust accumulation. The bag is not cleaned to bare fabric. It maintains a residual dust cake which tends to cause a pressure drop increase slowly over a long period of time during the life of the bag, which is about 2 to 5 years.[1]

A major consideration in the design and operation of baghouses is the maximum increase in pressure drop, as the dust cake builds up. If this pressure drop could be minimized, there would be a significant fan power savings. Another aspect of this filtration cycle pressure drop is the limit on gas flow. If the pressure drop could be reduced, the allowable gas flow could be increased. Reviewing the data that have been reported on electric power industry baghouses [1] suggests that the typical gas-to-cloth ratio for inside-to-out flow is about 0.01 m/s. For a full size utility bag 9 to 10 m long [2], with a diameter of 0.3 m, flow through each bag would be limited to about 6 m^3/min. The gas flow from a 500 MW capacity electric generating plant, assuming a reasonable gas flow rate of 100 m^3/min/MW of electric generating capacity, would require about 8000 bags. Reducing the number of bags could be the basis of a worthwhile capital saving.

Considerable work has been done on limiting the pressure drop rise during the filtration cycle. Much of the work has been related to making engineering changes to the fabric, improving the flow distribution and uniformity in the baghouse, and applying electrostatics.

Much research and development has been devoted to the application of electrostatics.[3] It has long been recognized that electrostatic charges and forces play a role in fabric filtration.[4] It has been claimed that the effects of electrostatics, mainly in the triboelectric properties of dusts and fabrics, are very important, if not critical, in controlling filtration properties. The work that was done by the various researchers involved:

- Charging particles prior to collection.
- Collecting particles in an electric field.
- Combining particle charging and collection.

From the reported work have come reports of significant pressure drop reductions.

Recent significant work that has made use of electric fields perpendicular to the flow, called electrostatically stimulated fabric filtration (ESFF), has been developed under the auspices of the United States Environmental Protection Agency. The ESFF concept makes use of electrodes which are placed axially, parallel to each other on about 20 mm centers. Electric fields of about 200-800 kV/m between adjacent electrodes are used; operation is below corona onset voltage. The electrodes were either in a harness (wrapped around a bag) or stitched or woven into the bag fabric. The work on ESFF has ranged from small laboratory baghouses, operating at temperatures

up to 150°C, to fairly substantial field pilot units.[5] Pressure drop reductions were usually about 40 to 50%.

A system for providing integral particle charging and collection in a combined electric and flow field (as shown in Figure 1) was developed as an outgrowth of earlier work on ESFF. In this system, sometimes called Advanced ESFF (AESFF), the corona discharge wire is axially located within the fabric bag, and the electric field is developed between the corona discharge wire and the bag. The bag is made conductive by including conductive yarns in the fabric during the weaving process. Alternatively, if the particulate matter is low in resistivity, it could make the bag sufficiently conductive so that it would be unnecessary to weave conductive yarns into the fabric. The generation of corona for charging and development of the electric field requires only one power supply. Except for its porous walls and closed ends, the device is similar to a wire-pipe ESP.

The system was tried on a small scale in a laboratory single-bag experimental baghouse at the U.S. Environmental Protection Agency's Air and Energy Engineering Research Laboratory at Research Triangle Park, North Carolina. A non-uniform deposition was observed to result in a reduced pressure drop over that of both conventional filtration and ESFF. It was found that pressure drops of 10 to 30% of that of conventional fabric filtration were being achieved.[5]

A decision was made to proceed with a field pilot plant evaluation. The pilot unit contained six bags, each 7.3 m long and 0.2 m in diameter. The spreader-stoker boiler, from which the slipstream was taken, typically had a large amount of unburned carbon in the fly ash. Preliminary measurements indicated that the resistivity was 1×10^5 ohm-m or less, sufficiently low so that three of the six bags, which were Teflon B® coated Fiberglas, had no provisions to increase their conductivity. The other three bags had stainless steel yarn woven into them longitudinally (axially). After 4 months of tests it was found that it was possible to operate at a pressure drop that was only 20 to 30% of that of conventional filtration. It was also shown that, for low resisitivity dust, there was no difference in performance between the non-conductive bag, which depended on particle matter conductivity, and the bags that had conductive yarn woven into them.[6,7]

A second pilot evaluation was undertaken with integral particle charging and collection in a combined electric and flow field at the EPA pilot baghouse at Southwestern Public Service where some of the earlier ESFF field pilot work had been done. The fly ash, from a pulverized-coal-fired boiler, had a considerably higher electrical resistivity than did the spreader-stoker fly ash. The bags that were used had woven-in stainless steel yarns, connected electrically to ground. This pilot unit is currently being operated.[8]

2. EXPERIMENTAL PROGRAM

A single-bag experimental baghouse at the EPA laboratory facilities at Research Triangle Park, North Carolina, was set up as shown in Figure 2 as a means of gathering the data to be used to develop an engineering design methodology for AESFF. Dirty-particle-bearing gas is introduced through the hopper and flows up into the bag, with the particulate matter deposited on the inner surface. The cleaned gas flows through the fabric and out of the baghouse (inside-out filtration). The fabric used for the filter bags was J.P. Stevens 648, a 570 g/m^2 Fiberglas cloth coated with 10% Teflon B®. This is a typical filtration fabric for reverse-air filtration. Some tests used the fabric in standard filtration form, with unmodified electrical conductivity. The electrical conductivity of these fabrics depended mainly on that of the materials plus the particulate matter that coats them when used. Other tests used a bag of the same material, except that the conductivity had been modified by having stainless steel yarns woven into the fabric. The yarns, running axially on 20 mm centers, each consists of 90 fibers of 316L stainless steel of 22 μm diameter.

The bags could be opened along the seam to allow removal from the baghouse and placement on a flat surface for examination and testing of the dust cakes that were deposited. The same bags were used over and over again for the various tests. The particulate matter that was used had been obtained, after collection in a baghouse, at the SWPS Harrington Power Station in Amarillo, Texas, which is the location of the second pilot plant. The size distribution of the undispersed SWPS fly ash was determined by outfitting a bag with a calibrated inertial cascade impactor inserted at mid-height. Under isokinetic sampling conditions, the mass geometric mean diameter was 3.3 μm, and the geometric standard deviation was 2.9. The charge-to-mass ratio of the redispersed SWPS fly ash was measured using this same test bag. On a total basis the fly ash was found to be almost electrically neutral.[9]

The baghouse arrangement, shown in Figure 2, was used to determine the effects of varying voltage, current, resistivity, temperature, and gas flow. Voltage was varied by changing the setting of the DC power supply. The voltages applied to the corona discharge wire were negative and ranged from 23 to 50 kV. The current was varied by changing the diameter of the corona discharge wire for different tests--sizes were 2.4, 3.2, 6.4, and 12.7 mm. Resistivity of the SWPS fly ash was changed by varying temperature and moisture. Negative corona was used because of the tendency of positively energized electrostatic precipitators to spark at lower voltages. This is the reason that negative polarity for the corona is used almost exclusively in modern precipitators. The temperatures were 21°, 82°, and 149°C. A temperature of 149°C is similar to that of many coal-fired steam-electric power plants. Moisture levels were varied from about 1% to slightly more than 9%. Moisture levels of 6 to 9% are the range in which most coal-fired boiler gases operate.[10]

After each test run the bag would be removed and opened, and measurements made of areal density, dust cake thickness, and permeability. Afterwards the bag would be cleaned and put back into the baghouse for the next test. The average clean bag drag was 660 Pa/m/s. Drag (resistance-to-flow) is the reciprocal of permeability.

Figure 3 is a typical set of test results. For this test run the electric field was 750,000 kV/m, the average current density was 3×10^{-5} A/m^2, and the gas-to-cloth ratio was 0.02 m/s. The axis labeled "Distance along Electrode" is that portion of the fabric filter bag near the corona discharge electrode between the lower oval weight and the upper oval termination of Figure 2. The drag, areal density, and dust cake thickness were measured independently. The dust cake density was computed from the areal density and dust cake thickness.

The preliminary conclusions of the single-bag tests were:

1. The drag decreased with increasing distance along the electrode--the highest drag was at the inlet.

2. The drag always decreased with decreasing areal cake density and dust cake thickness.

3. There was no correlation between drag and dust cake density. Sometimes the dust cake density decreased with decreasing drag. At other times it would remain relatively constant or even increase.

In addition, a very useful conclusion that was drawn was that the face velocity, which is the permeability (or typically inverse of the drag), generally increased linearly as a function of position, as shown in Figure 4.

3. ENGINEERING DESIGN MODEL DEVELOPMENT

The mathematical model which had been developed [9], for fabric filtration with integral particle charging and collection in a combined electric and flow field, had

to consider two types of particle collection--the portion due to gas as porous flow through the fabric and the portion due to electrostatic precipitation. The particle collection due to the electrostatic precipitation effect required knowing if the flow was turbulent or laminar. If turbulent, the particle collection would be expressed by the Deutsch-Anderson equation. If laminar, a simpler collection relationship could be used.[10] The inlet velocity for a full size commercial bag is of the same order as is the gas flow velocity in an electrostatic precipitator, which usually has turbulent flow. This suggests that a fabric filtration baghouse might also have turbulent flow, especially near the inlet.

The linearity of face velocity with a position, as shown in Figure 4, allowed a relationship to be developed for the velocity as a function of position in the bag. This subsequently allowed the Reynolds number to be computed as a function of the product of the average gas/cloth ratio, $\bar{v}_f$, and bag length, L, for parameters of position in bag, z, as seen in Figure 5. Fabric filtration bags of the length and average gas/cloth ratios used in commercial practice operate in the region above the turbulent-to-laminar transition, commonly accepted as a Reynolds number of 2100. The small bags used in the laboratory were operating below a Reynolds number of 2100 and were consequently operating in the laminar regime. Therefore for a practical model, the electrostatic precipitation collection was assumed to be taking place in the turbulent flow regime.

The two particle collection mechanisms--porous flow and electrostatic precipitation--require that a bag be divided into a number of length increments. For each increment the amount of particulate matter collected is

$$N_{j-1} [(1 - H_j) G_j + (1 - G_j) H_j] = N_j \qquad (1)$$

in which N_{j-1} is the total amount of particulate matter entering the j increment, and N_j is the amount of particulate matter exiting to the j+1 increment.

In Equation (1), G_j, which is the fraction of the particulate matter collected due to porous flow, is

$$G_j = \frac{(v_{j-1} - v_j) \frac{\pi b^2}{4}}{v_{j-1} \left(\frac{\pi b^2}{4}\right)} = \frac{v_{j-1} - v_j}{v_{j-1}} \qquad (2)$$

in which v_{j-1} is the velocity of the gas entering the j increment, and v_j is the velocity of the exiting gas. The quantity $\pi b^2/4$ is the cross sectional area of the bag having a diameter b. The velocity of the gas entering and exiting the increment is computed by the expression for velocity, previously mentioned, that had been based upon the assumption of a linear increase in face velocity as a function of position.

The fraction of the dust collected by electrostatic precipitation, H_j, makes use of the Deutsch-Anderson collection equation

$$H_j = \sum_{i=1}^{m} \{1 - \exp(-\overline{SCA}_j \cdot w_{ji})\} \qquad (3)$$

in which the average specific collector area, $\overline{SCA}_j$, is the ratio of the collecting area to the gas flow, and w_{ji} is the electrical migration velocity. The index i is the ith particle size increment. The derivation of the Deutsch-Anderson equation assumes that the migration velocity is a constant for all particles, which requires that the size distribution be divided into a number of individual size increments.

In Equation (3), the average specific collector area, $\overline{SCA}_j$ is

$$\overline{SCA} = \frac{\pi bL/l}{\frac{v_{j-1} + v_j}{2} \cdot \frac{\pi b^2}{4}} = \frac{8L}{bl(v_{j-1} + v_j)} \tag{4}$$

in which b is the bag diameter, L is the bag length, l is the number of length increments, and the inlet and outlet gas velocities are v_{j-1} and v_j, respectively.

The electrical migration velocity, w_{ji}, is

$$w_{ji} = \frac{2a_i b\epsilon_o E_1 E_2 J \ln \frac{L + z_j}{L - z_j}}{\eta(bJ \ln \frac{L + z_j}{L - z_j} + 32\epsilon_o E_3 \overline{v_f})} \left[1 - \exp \frac{(-\frac{9}{16}\eta b \ln \frac{L + z_j}{L - z_j})}{a_i^2 \rho \overline{v_f}} \right] \tag{5}$$

in which a_i is the ith increment particle diameter, b is the bag diameter, ϵ_o is the permitivity of free space, E_1 is the charging electric field, E_2 is the collecting electric field, E_3 is the electric field near the bag surface, J is the average current density, L is the bag length, η is the gas viscosity, ρ is the particle density, $\overline{v_f}$ is the average gas-to-cloth ratio, and z_j is the location of the mean distance of increment j from the bag inlet.

In the development of Equation (5), it is assumed that the particle enters the bag with zero charge. The charge builds up and approaches saturation as the particle travels up the bag. The time term that appears in the basic expression for migration velocity [10] had been related in the derivation to the expression for gas velocity that had been described previously. Finally, in the development of Equation (5) it is assumed that the only charge carriers are ions.

Figure 6 shows the computation for the non-uniform particulate matter deposition for the bag geometry, electrical conditions, and particle size distribution for the test conditions of Figure 5.

Figures 7 and 8 show the model computation for the two pilot plant tests. The bag geometry and electrical conditions are stated for each. The fly ash, for the field pilot test of Figure 7, is the same as was used for the single-bag laboratory tests: the geometric mass mean diameter was 3.3 μm, and the geometric standard deviation was 2.8. The pilot test, for which the computation of Figure 8 was performed, was for a spreader-stoker furnace whose fly ash had a geometric mass mean diameter of 18.4 μm and a geometric standard deviation of 5.2.

Of specific interest is the dominant effect of electrostatic precipitation collection within the bag. In conventional (non-electrified) filtration, the collection in each increment would be uniform and would all be due to porous flow.

The model was extended to predict the relative pressure drop of an electrified fabric filtration bag in respect to a bag with a non-uniform deposit. The relationship for drag or resistance to flow, S, is

$$S = k_2 W = \frac{\Delta P}{v_f} \tag{6}$$

in which k_2 is the specific cake resistance, W is the areal density, P is the pressure drop across the dust cake, and v_f is the face velocity. If it is assumed that k_2 does not vary with either dust cake thickness or electrified vs. non-electrified condition (11), then the average drag for the non-uniform deposit, $\bar{S}_n$, is

$$\bar{S}_n = \left(\sum_{j=1}^{1} \frac{1/1}{S_j}\right)^{-1} = 1\left(\sum_{j=1}^{1} \frac{1}{k_2 W_j}\right)^{-1} = 1k_2 \left(\sum_{j=1}^{1} \frac{1}{W_j}\right)^{-1} \tag{7}$$

In Equation (7), 1 is the number of increments, S_j is the drag for the j increment, k_2 is the specific cake resistance, and W_j is the areal density of the j increment.

It follows from Equations (6) and (7) that

$$\frac{\Delta P_n}{\Delta P_u} = \frac{\bar{S}_n}{S_u} = \frac{1\left(\sum_{j=1}^{1} \frac{1}{W_j}\right)^{-1}}{W_u} \tag{8}$$

which, for non-uniform and uniform deposition, relates the relative pressure drop, $\Delta P_n/\Delta P_u$, to the ratio of the average drags, and to the ratio of the average areal densities.

The relative pressure drop computed by Equation (8) for SWPS, the pilot unit of Figure 7, was 0.44, which compares to a measured value of 0.43.[11] For the spreader-stoker pilot unit of Figure 8, the computed relative pressure drop was 0.22 which compares quite well to a measured value of 0.20 to 0.30.[6]

4. CONCLUSION

A mathematical engineering design model has been developed that predicts the non-uniform particulate matter deposition and relative pressure drop, compared to conventional or non-electrified deposition for fabric filtration with integral particle charging and collection in a combined electric and flow field. The model prediction appears to be reasonably accurate on the basis of limited pilot plant data.

The mathematical engineering model which relates performance to electrical conditions, bag geometry, and particle size distribution is a design tool that can be useful in further development of this new technology.

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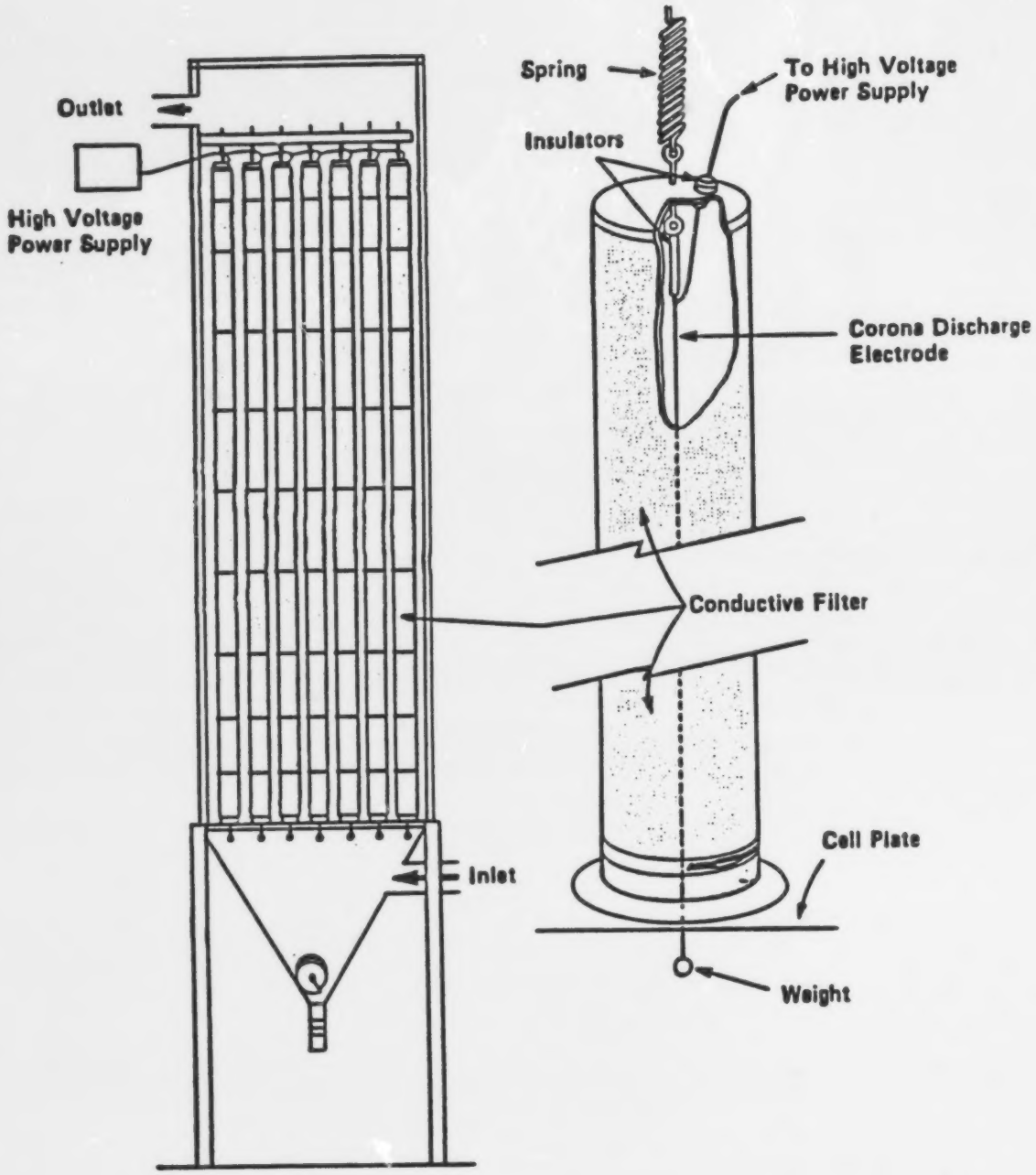

Figure 1. Integral Particle Charging and Collection in a Combined Electric and Flow Field.

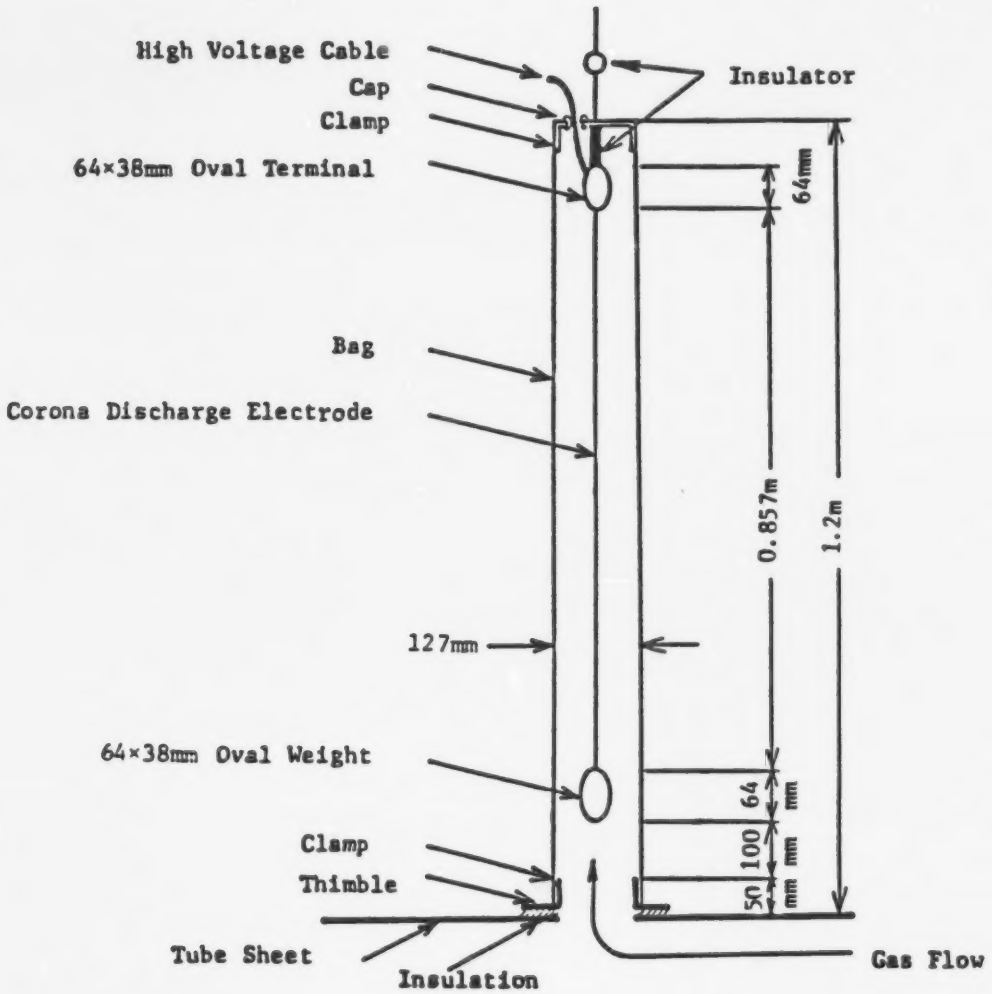

Figure 2. Single-Bag Experimental Baghouse Setup.

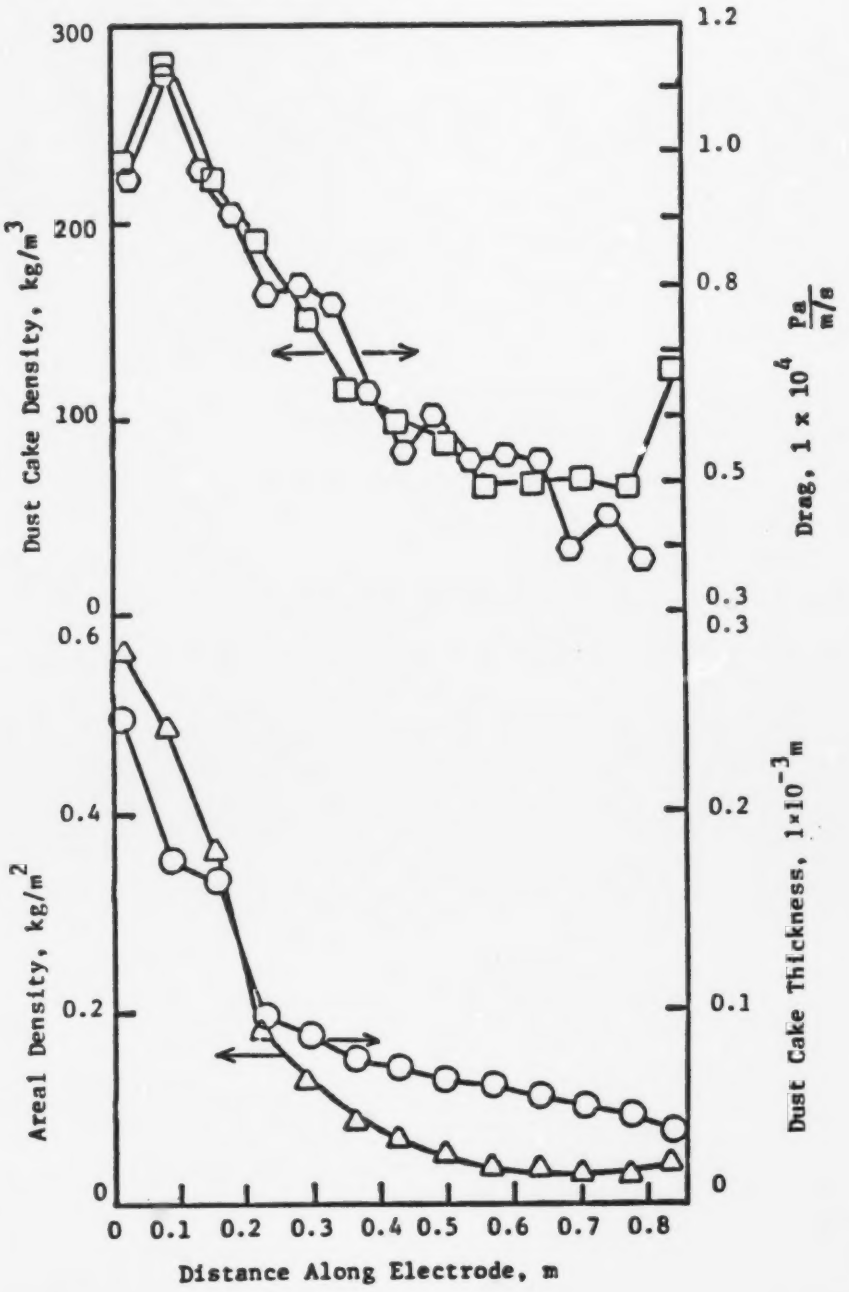

Figure 3. Test Run Results on Laboratory Setup for an Electric Field of 750 kV/m and a Current Density of 3 x 10^{-5} A/m^2.

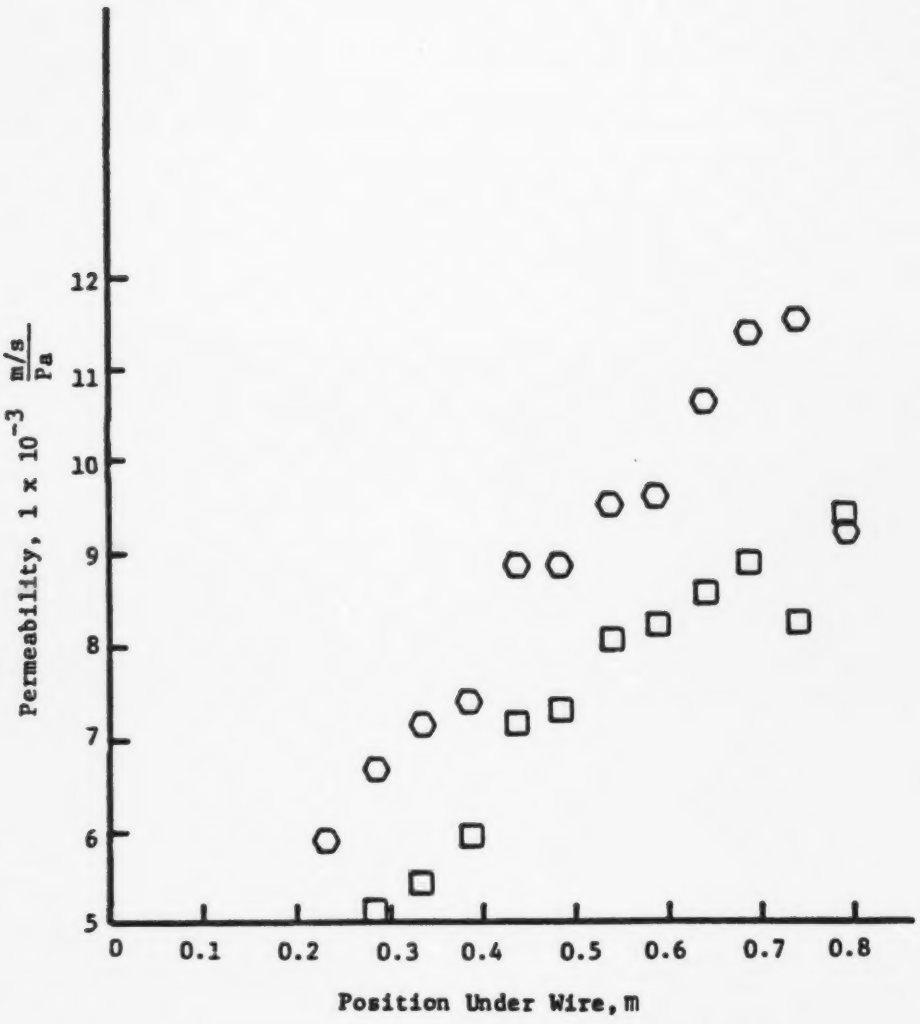

Figure 4. Examples of Linearity of Face Velocity at Unit Pressure vs. Position Under Corona Wire.

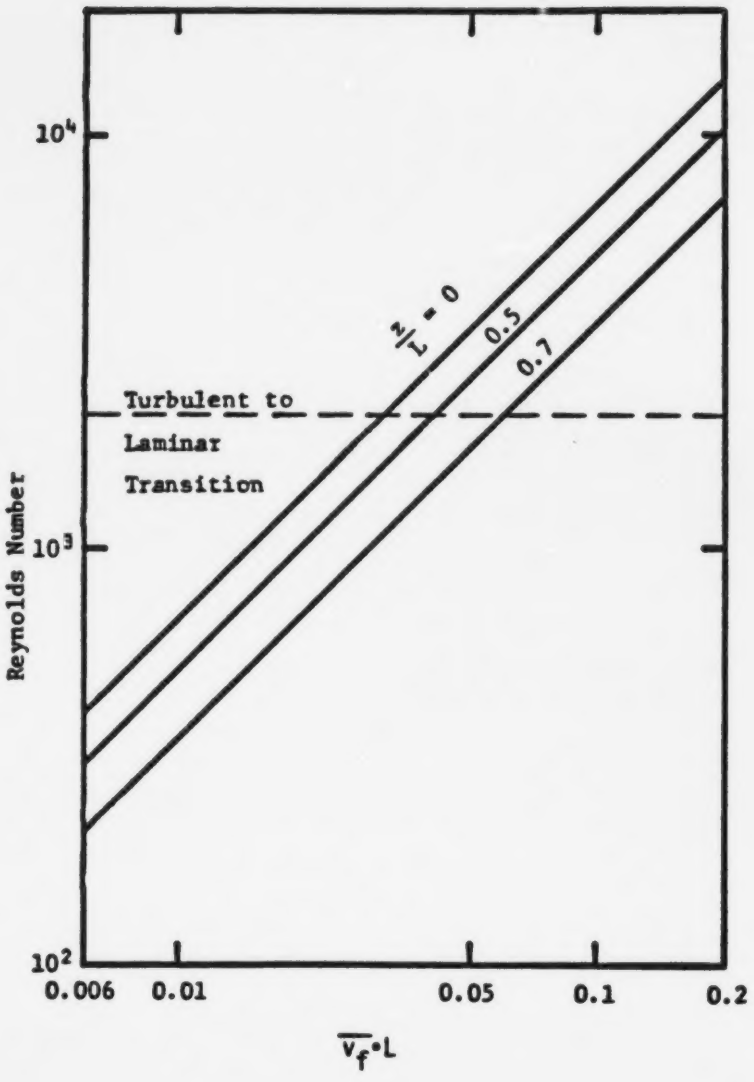

Figure 5. Reynolds Number as a Function of the Gas-to-Cloth Ratio, $\overline{v}_f$, and Bag Length, L, for Parameters of Position in Bag, z.

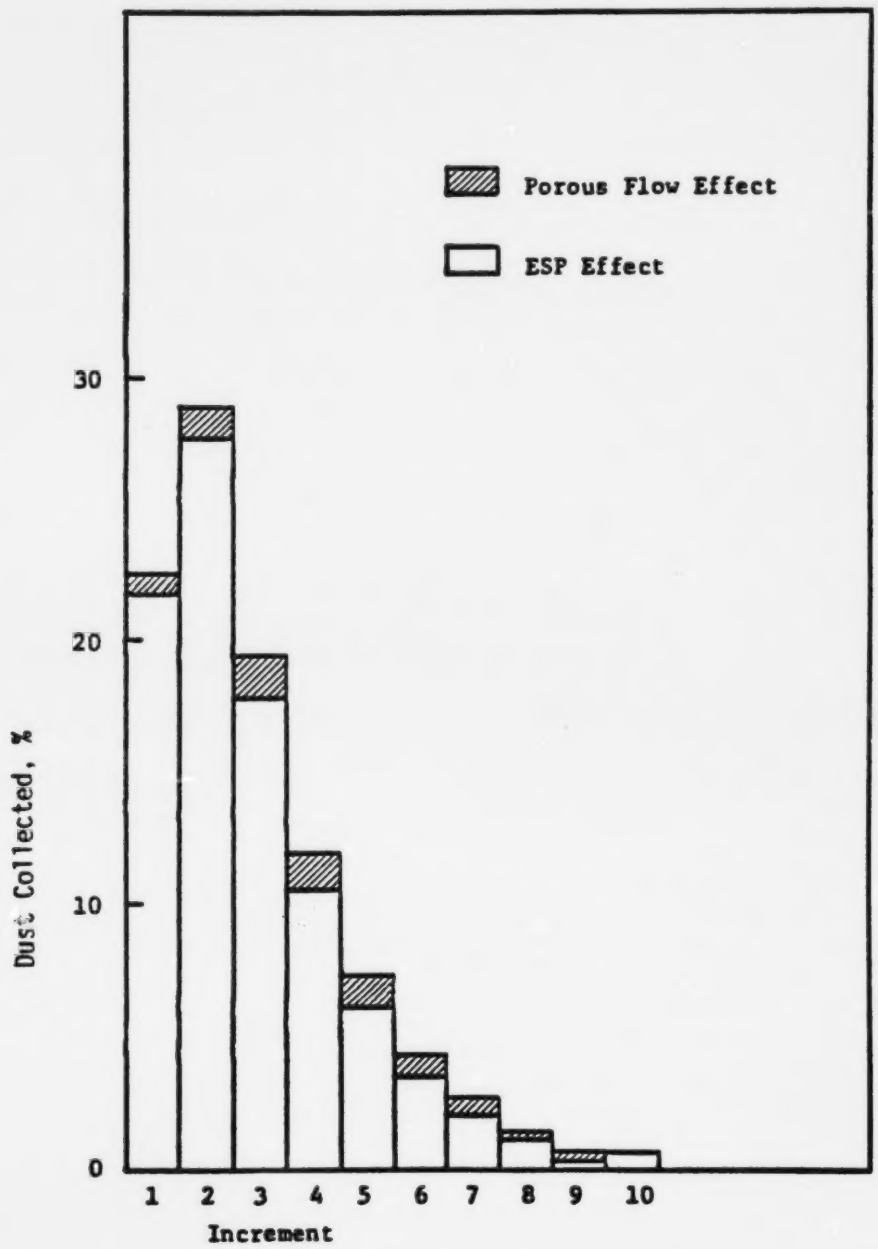

Figure 6. Mathematical Model Prediction of Non-uniform Distribution for an Electric Field of 750 kV/m and a Current Density of 3×10^{-5} A/m^2.

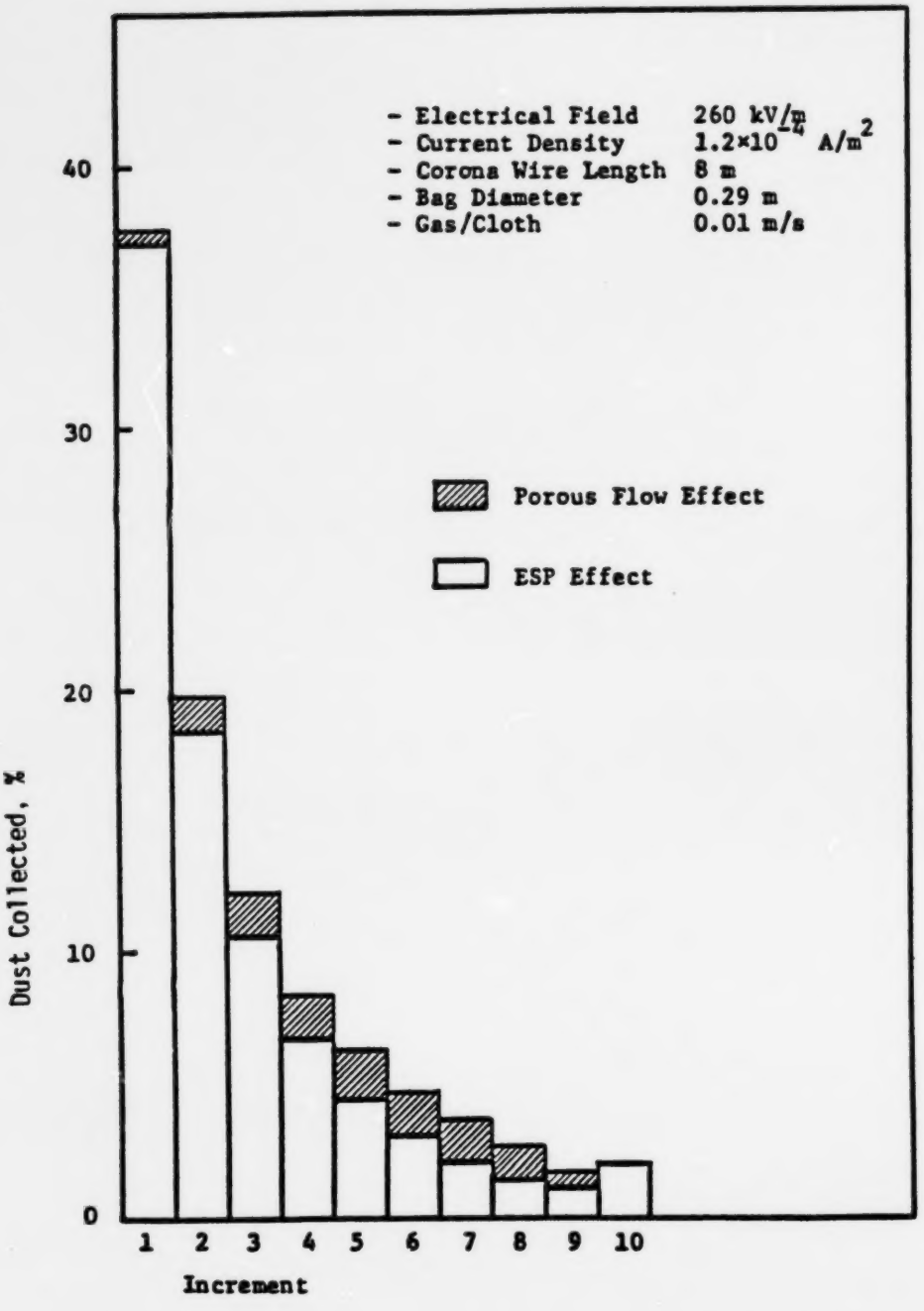

Figure 7. Mathematical Prediction of the Non-uniform Distribution Using the SWPS Pilot Unit Electrical Conditions.

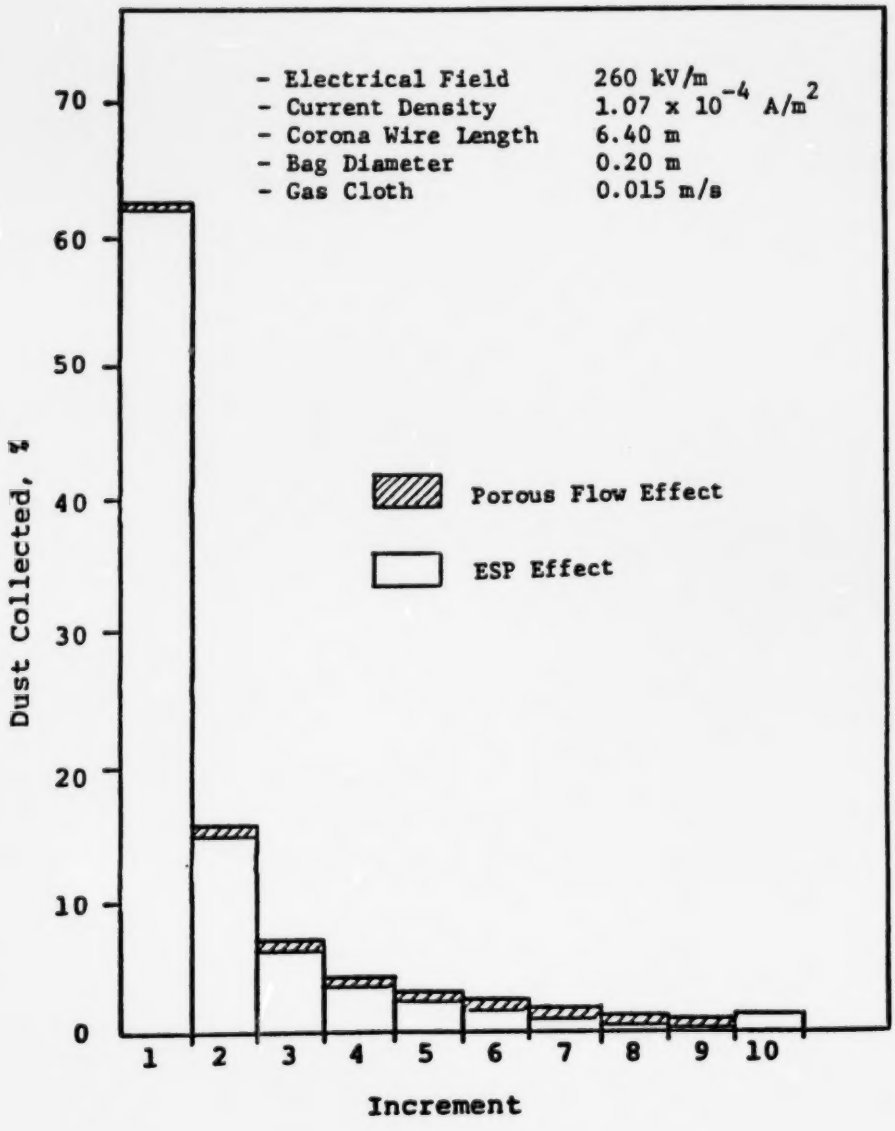

Figure 8. Mathematical Model Prediction of the Non-uniform Deposition for the Spreader-Stoker Pilot Unit Electrical Conditions.